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MULTI-BAND AUTOMATIC SUN AND SKY SCANNING RADIOMETER SYSTEM FOR MEASUREMENT OF AEROSOLS

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ABSTRACT:

A weather resistant automatic scanning sun photometer system is assessed and demonstrated as practical for measurements of aerosol concentrations and properties at remote sites. Interfaced with a transmitter using the Geostationary Data Collection System, the data are processed in near real-time. The processing allows a time dependence of the aerosols and water vapor and an ongoing assessment of the health and calibration of the instruments. The systems automatic data acquisition, transmission and processing offer immediate application to atmospheric monitoring and modeling on a regional to global scale and validation of Satellite retrievals. We estimate that under normal circumstances the retrieved aerosol optical thickness has a network wide accuracy of ±0.02 from 340 nm to 1020 nm, water vapor ±0.2 cm and size distribution from 0.1 to 3. µm.

KEY WORDS: Sun Photometry, Aerosols, Optical Thickness, Radiometer

1 - INTRODUCTION

Ground based atmospheric aerosol measurements using sun photometry has changed little since Voltz (1959) introduced the first handheld more than three decades ago. Modern units can collect data more accurately and quickly but the method remains largely the same, that is a filtered detector measures the extinction of direct beam radiation according to Beers Law:

$$V = V_0 exp\text{-}(\tau m) \qquad (1)$$

where:
V=Digital voltage
Vo=extratrestrial voltage
m=optical airmass
τ=total optical thickness

Other strategies have been developed and are commercially available. The shadow band radiometer measures spectral total and diffuse radiation to obtain the direct component from which aerosol optical thickness is computed. The instrument has been shown to be reliable over long periods of time and is widely used for high volume data collection programs (Harrison et al., 1994). Sky scanning radiometers have also been used to derive the aerosol optical thickness and more importantly the aerosol properties such as size distribution and phase function.(Nakajima et al. (1983), Tanré et al. (1988), Shiobara et al. (1991) and Kaufman et al., (1993)). This technique requires precise aureole measurements near the solar disc and extremely good collimation. Unfortunately most systems have been rather cumbersome and beyond the scope of many investigators resources however the following description of a new sun and sky scanning spectral radiometer overcomes most such limitations providing the first of a three component monitoring system.

The second and often neglected component of sun photometry systems is that of data handling including delivery of the raw data to a central archive and its subsequent processing and availability to the user. We have utilized the simple and inexpensive Data Collection System used by GOES, METEOSAT and GMS which provides global coverage in near real time at very little expense (NOAA/NESDIS, 1990).

Finally there are the very contentious issues of processing the data archive. Although Beers law is very straight forward, its implementation has as many variations as there are investigators who use it. The central problem being agreement on the accuracy which the aerosol optical thickness is derived. The uncertainties in computation of the airmass (m), the calculations for the Raleigh, ozone and water vapor optical depths (τ_r, τ_o and τ_w) as well as strategies for calibration of the instruments and monitoring the long term change in calibration all combine to preclude any globally accepted processing scheme. Our near term solutions make the original data available to everyone and provide a basic processing package available to all users with sufficient friendliness and flexibility that all data may be accessed globally through common forms of electronic communication.

Following is our version of a ground based aerosol monitoring system that addresses, compromises and offers a solution to the three components of a sun photometer network system. We suggest that future networks must integrate all three components if they are to be successful and which is dependent on further development of the individual parts. We have assembled a reliable system and offer it as a point of focus for further development of each component. As an example of the system's performance we present data collected in the Brazilian Amazon during the dry season of 1993. Owing to the fundamental importance of these and similar data for basic and applied research, our philosophy is for an open, honor system whereby all contributed data may be accessed by anyone but publication of results requires permission of the contributing investigators.

2 - AUTOMATIC SUN AND SKY SCANNING SPECTRAL RADIOMETER

Most if not all sun photometer networks have had limited success when people are required to make routine observations. Therefore an automatic instrument is a fundamental component to any network where routine observations are required. Additionally the instrument protocol must be reasonably robust such that the data that are not wanted can be screened from that which are useful. Lastly the instrument must collect data for monitoring its calibration. Following is our assessment of an instrument that meets these criteria and our requirements of a field hardy sun and sky scanning spectral radiometer. The reason for a sky scanning radiometer rather than a traditional sun photometer is to provide duplicity in aerosol optical thickness retrievals and aerosol properties from inverting sky radiance data.

2.1. General Description

The Cimel Electronique 318A radiometer manufactured in Paris, France is independent of public electrical and communication systems. This instrument has a 1.2 degree full angle field of view, dual detector for measurement of direct sun, aureole and sky radiance with 33 cm collimators for 10^{-5} straylight rejection. The sensor head is mounted on the robot such that the optics are protected from rain and entrance of foreign particles into the system in the non active position. The sun aureole collimator is protected by a quartz window allowing observation with a UV enhanced silicon detector with sufficient signal to noise for spectral observations from approximately 300 nm to 1020 nm. The sky collimator has the same field of view but an aperture approximately 10 times larger for better dynamic range for the sky radiances. The components of the sensor head are o-ring sealed from moisture and desiccated to prevent damage to the electrical components and interference filters. Eight interference filters are located in a filter wheel which is rotated by a direct drive stepping motor. A thermister measures the temperature of the detector allowing compensation for any temperature dependence in the silicon detector.

The sensor head is pointed by direct drive step by step azimuth and zenith motors with an accuracy of 0.05 degrees. A microprocessor computes the position of the sun based on time and input locational coordinates and directs the sensor head to approximately one degree of the sun after which a four quadrant detector tracks the sun precisely prior to a programmed measurement. After the routine measurement is completed the instrument returns to the "park" position awaiting the next measurement sequence. A "wet sensor" exposed to precipitation will cancel any measurement sequence in progress.

The data are downloaded under program control to a Data Collection Platform (DCP) typically used in the geostationary satellite telemetry system. See section 3.

2.2. Measurement Concept

The radiometer has sufficient S/N that observations can be made from 300 to 1030 nm as currently configured. The basic sun measurement is three spectral observations (triplet) taken 30 seconds apart. Triplet observations are made during morning and afternoon langley calibration sequences and at 15 minute intervals in between. The time variation of clouds is typically greater than that of aerosols and would manifest itself in an observable variation in the raw digital data. Additionally the 15 minute interval allows a longer temporal frequency check for clouds.

Two basic sky measurement sequences are the almucantar and principle plane. The almucantar is a series of measurements taken at a constant view zenith angle and specified azimuth angles relative to the position of the sun. During a measurement sequence for one of four channels the instrument makes a sun measurement, begins the aureole measurement sweep through the solar disc and continues through 360 degrees of azimuth in about 40 seconds. The almucantar sequence is typically made at an optical airmass of 2 or less to maintain large scattering angles.

The principle plane sequence operates in much the same manner but in the principle plane of the sun. Because the scattering angles are constant with solar zenith these observations are made for optical airmasses between 2 and 1 when the almucantar measurements are less effective.

2.3. Instrument Stability and Calibration Accuracy

We define the stability of the instrument as its ability to accurately reproduce results from multiple measurements under constant conditions using standardized techniques. This is best measured by examining the instrument output under conditions required for instrument calibration. A two meter integrating sphere at Goddard Space Flight Center is used to calibrate the sky radiance channels and mountain top langley plots are used for the sun channels.

Our field calibration instrument has been in almost continuous operation since March 1993. Dark current values show a variation of ±1 count compared to typical values of 2000 to 15000 counts depending on optical depth and airmass. With respect to the long term stability of calibration, two measurements taken eight months apart have been made to date at NASA Goddards integrating sphere facility. Assuming the absolute calibration of the sphere is known exactly, the calibration of the instrument has decreased by about 1 to 5% depending on channel. This is less than or equal to the absolute accuracy (±5%)of the integrating sphere.

Langley calibrations were made on Mt. Lemmon near Tucson Arizona in May 1993 and December 1993. The change in zero airmass voltage between the two dates was 2.3% at 1019 nm and 0.5 to 1.1% for all other channels. These results are typical for interference filters

Measurements of the spectral temperature sensitivity of the instrument showed the results agreed with the published temperature sensitivity of the detectors and that only the 1019 nm channels showed significant temperature variation (0.25%/^{o}C) warranting a correction to a reference temperature in the processing.

3 - DATA TRANSMISSION

Data are transmitted from the memory of the sun photometer via the Data Collection Systems of either of three geosynchronus satellites GOES, METEOSAT or GMS to the appropriate ground receiving station. The data can be retrieved for processing either by modem or internet resulting in near real-time acquisition from almost any site on the globe. The DCS is a governmental system operated for the purpose of transmitting low volume environmental data from remote sites for various institutions and government agencies.

Each station on the GOES and METEOSAT networks has been assigned a transmission window allowing approximately 30 kbytes per day in twenty four individual transmissions at hourly intervals. During each transmission, a packet of data and status information are time stamped by the radiometer, the DCP and the central receiving station (Wallops Island, VA, USA for GOES, Darmstadt, Germany for METEOSAT and Tokyo, Japan for GMS). Typically the data are maintained in the receiving station computers for 3 to 5 days before they are overwritten. We retrieve the data daily from the central receiving station which we term near real-time.

3 PROCESSING SYSTEM

The third fundamental component of a sun photometer network is a friendly software package that provides near real-time information on the health and calibration of the instruments, provides state of the art processing of the data, provides an orderly archive of the data and provides easy access for all users to that data base. The automatic radiometer and DCS transmissions allow these software goals to be developed. We shall discuss these aspects of the current operational state of the software and future directions.

3.1. Instrument and Network Health

The radiometer data stream includes date, time, temperature, battery voltage, wet sensor status and time of transmission as well as several levels of identification numbers. The DCP adds a time stamp at the time of transmission as does the DCS receiving station plus checks for parity errors and signal strength of the transmission. When the data are downloaded from the central receiving station, these data and information are used to automatically generate a status report and a trouble shooting report both of which are automatically emailed to appropriate system managers. The status report provides a comprehensive assessment of the operation of the radiometer and DCP for the data transmitted with the current download. Network managers then have sufficient information to assess the operation of individual stations. To more quickly identify trouble spots, a troubleshooting report is generated that lists by instrument only information that fails to meet normal operating thresholds i.e.. low battery voltage, transmission time error, missed transmission etc. This approach can identify problems with a remote station often leading to same day resolution. Previously this would have been possible at only the most sophisticated sun photometer facilities.

3.2. Data Processing

Data processing includes both the Beer's Law of standard sun photometry and rather sophisticated aureole inversions required for the present day radiometer instrument. Standardization is complicated by the lack of agreement on corrections, calibration procedures etc. often caused by divergent error tolerances or requirements of various investigators. We have assembled a series of processing algorithms running under X-WINDOWS that meets simple criteria which are that the algorithms have been published in the open literature and are generally accepted in the scientific community. We have assembled these algorithms into one primary program called "demonstrattttt". The algorithms are accessed in the program under three principle categories, calibration, time dependent sun retrievals, and sky radiance retrievals. There are a growing number of sub processing algorithms from each of these.

3.2.1. ***Calibration.*** Calibration of sun photometers historically has limited the wide scale deployment and long term reliability of these data. A number of strategies exist which have been implemented for calibrating the direct sun observation most of which are a variation of the Langley method. Other methods rely on a combination of direct sun and aureole langleys. A third method is a simple inter-comparison.

The radiometer makes a langley data collection each morning and afternoon between an optical airmass of 2 and 7. The interactive calibration routines allow deselection of points and tabled Vo's recomputed and displayed with each deletion. The Vo's may be applied to the original langley data and aerosol optical thickness plotted as a function of time or airmass in two additional windows for further inspection of the quality of the langley. The calibration for the modified langley for water vapor (Bruegge et al., 1992 and Reagan et al., 1992) and Dobson UV channel pair for ozone retrieval is performed in much the same way. This method is typically used for the mountain top langleys for absolute calibration.

An automatic calibration is also made on all langley data with aerosol optical thicknesses less than 0.1 at 670 nm. An iterative algorithm computes the regression and drops all local minimums more than 10% below the regression. The iteration continues until no more local minimums are identified. The resultant Vo is then stored into a file and plots them as a time dependence for that instrument. Note that these data are noisy and are used only for identifying trends in the calibration decay between absolute mountain top calibrations.

A second approach ratios various spectral combinations of the langley data sets and plotted as regular langleys (Forgan, 1993). This approach is applicable for higher optical thickness conditions. Only minimal triplet screening is required to eliminate cloud conditions. The Vos are computed, archived and plotted against time. Again this is used as a trend indicator between absolute mountain top calibrations. The advantage over the previous method is the significantly greater number of points available for trend analysis.

Intercomparison of automatic instruments is easily accomplished by a routine that searches a specified portion of the data base. Having met criteria for a space and time match, sun and sky data are automatically inter compared and a table of old and new calibration coefficients is generated. Aureole corrected langley plots analysis (Nakajima, 1986) has not been implemented at this writing.

3.2.2. ***Time Dependence.*** The time dependence window serves as the access point for all other windows. The aerosol optical thickness, precipitable water, wavelength exponent and calibration trends as well as the status indicators may be plotted as a function of time in this window. For a particular instrument and location, all or part of the data may be displayed by interactive cursor subsetting. For example the dry season data (June to October) from Cuiaba Brazil clearly shows the increase in aerosol optical thickness as the burning season commences in August (Figure 1). Subsetting to one day of data brings new features to the screen (Figure 2). The GMT time scale in hours is displayed, a color scale of local time is drawn, mean 15 min. sun observations are plotted and almucantar (triangles) principle plane (squares) and successful inversions (circles and x's) are shown under the time scale. A hatched line above the time scale indicates langley data and green vertical bars inside the plot indicate that the wet sensor has been activated and no sun data are available. Individual points may be de selected in this window.

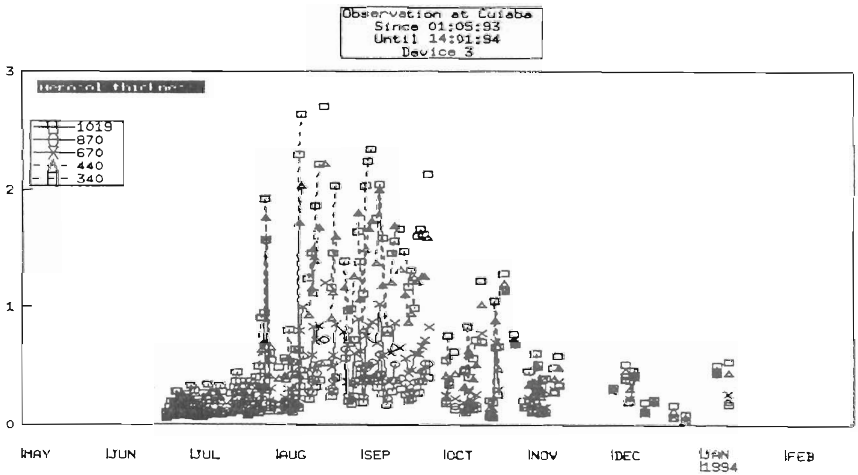

Figure 1, The aerosol optical thickness dry season record showing the increase in aerosols in August due to regional burning.

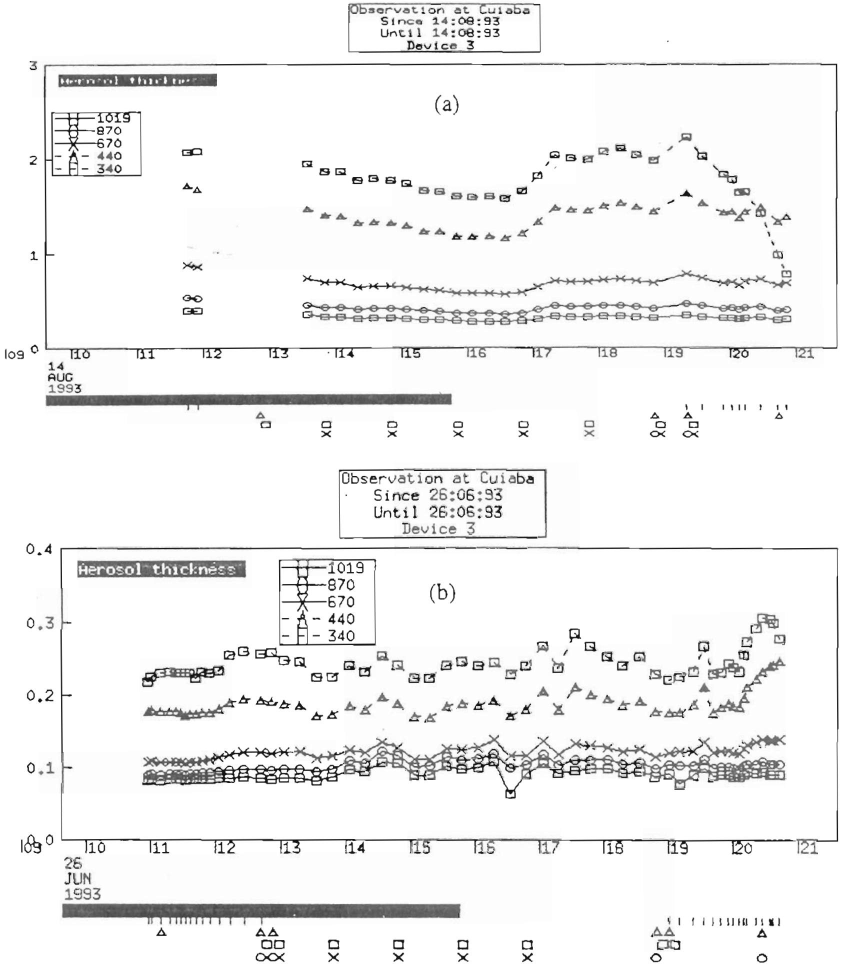

Figure 2, The aerosol optical thickness on August 14 (a) shows significant aerosol loading in contrast to June 26 (b). Note the addition of time dependent information on the abscissa including almucantar (Δ),principal plane(□), inversion (o or x) and Langley data (|).

3.2.3. *Sky Radiance Inversions.* The almucantar window displays the four channel sky radiances as a function of scattering angle, volume size distribution from 0.1 to ~3. µm, scattering phase function and a status table of the aerosol optical thickness and wavelength exponent computed from both direct sun and the aureole measurements (Fig 2). Additionally the spectral asymmetry factor is computed from the phase function. From the radiance data, a window may be opened with zoom capabilities which separates the four spectral sky radiance bands into single color coded bands allowing close inspection of the data. The program automatically checks the quality of the almucantar data by examining the symmetry of the measured radiances about the sun. If the angular asymmetry exceeds 10%, those pairs are removed from the inversion process. If the integrated asymmetry exceeds 10% or there are not a sufficient number of data points, the data are not inverted. The inversion routine used is that of Nakajima, (1983) and has a number of options that will be implemented over time.

The principle plane data are processed using the same inversion however only data on the zenith side from the solar disc are used in the inversion due to asymmetry induced by the ground reflectance. The principle plane window has identical capabilities as the almucantar window. The test for the quality of the data is simply the smoothness of the curve.

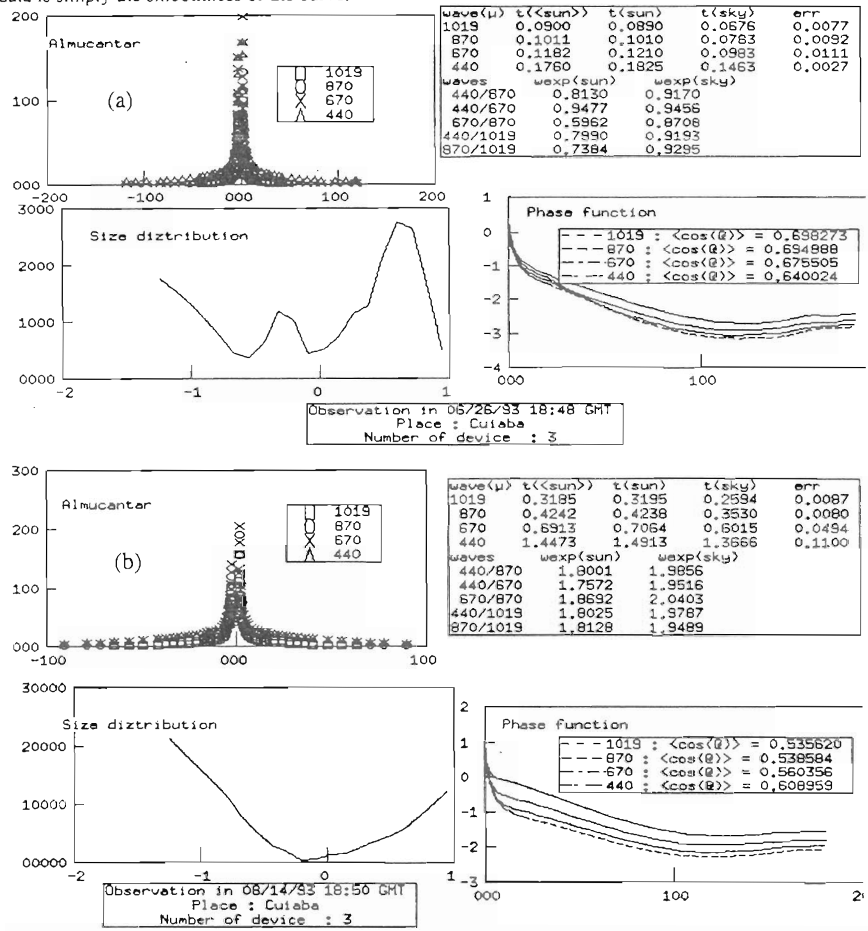

Figure 3, A successful inversion of almucantar radiances during clear (3a) and hazy (3b) conditions is possible when the data are symmetric about the sun (upper left plot within window). Inversions produce a volume size distribution with good accuracy from 0.1 μm to about 3 μm aerosol radii. The aerosol optical thickness and phase function (right side of window) from the aureole inversion are also computed using Nakajima's (1983) code.

3.2.4. ***Down welling Flux.*** In addition to aerosol properties and concentrations we have incorporated an empirical spectral cloud free flux model (Bird and Riordan, 1986) to compute from the measured aerosol and water vapor measurements the total, direct and diffuse down welling flux in the total solar spectrum and photosynthetically active radiation (PAR) bands. Single scattering albedo and ground reflectance are the only parameters which the instrument does not measure and which are required inputs. The interactive computations are made for any instantaneous or time dependent measurements. The window displays the spectral flux curves for the total, direct and diffuse irradiance and a summary box gives integrated values for each component of the broad band and PAR. The model is applied to the time dependence creating a data set of integrated fluxes. Options exist to compute coincident fluxes for user specified background conditions. Ratios of ambient vs background conditions are computed and displayed in a summary box.

Incorporation of more rigorous radiative transfer models is planned.

3.3. Cloud Screening

Data are taken by the automatic instruments under all non precipitation conditions causing significant cloud contamination in the raw data. The philosophy for using the data base within "demonstrattttt" is to provide primitive cloud screening based on the variability of the triplets that allows some cloud contaminated data to be displayed. Further refinements to the screening process may be made by manual deselection of the contaminated data through cursor control on the time dependent window allowing the data set to be cleaned and downloaded if desired.

Automatic cloud screening of the almucantar and principal plane data are by symmetry and smoothness checks respectively of the data about the solar disc as explained in section 3.2.3.

3.4. Downloading Data

Labeled spreadsheet export files may be created of all data in the data base and all data generated in the "demonstrattttt" processing program. Data for export may be selected by location, time, and the type of raw or processed data desired. The data may be downloaded to any computer with internet access using a guest account. For further access information send a request to sunphoto@kratmos.gsfc.nasa.gov.

3.5. Data Accuracy

The data accuracy of the aerosol optical thickness and water vapor retrievals is a function of the knowledge of the calibration accuracy, cloud contamination and the variability of the instrument. From section 2.3 the instrument variability is for all practical purposes insignificant and will not be displayed as error bars. The variability of the atmosphere is characterized by the variability of the triplet optical thicknesses which may at times be cloud contaminated. This variability will be plotted as error bars on the time dependence. The uncertainty due to calibration will be tracked with all time dependent data through a second set of error bars plotted on request and a dialogue box that tracks the calibration sequence to a time dependence between and/or to the nearest mountain top langley.

The uncertainty of the sky radiance data is more difficult to ascertain since these only constitute single observations and no absolute self-calibration procedure is implemented between the sphere calibrations. Based on the sphere calibration the uncertainty in the sky radiance is $\pm 0.05\ \mu w/cm^2 \mu m/str$ for all four channels at the time of calibration.

4 - CONCLUSION

We believe that a successful system for long term monitoring of aerosols requires automatic low maintenance radiometers, real time data reception and processing as well as an easily accessible data base for the scientific community. We have developed a system of commercially available hardware and public domain software that has yielded regionally based aerosol amounts and properties in North and South America. Systems will come on-line in 1994 what will accommodate global monitoring and intensive field campaigns. The philosophy of an open interactive data base is expected to promote research and collaboration among investigators

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